

NASA TECHNICAL TRANSLATION

NASA TT- 20171

11-24
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APPLICATION OF COPPER-CARBON FIBER COMPOSITES
TO POWER SEMICONDUCTOR DEVICES

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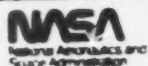
{NASA-TT-20171} APPLICATION OF
COPPER-CARBON FIBER COMPOSITES TO POWER
SEMICONDUCTOR DEVICES (NASA) 18 p CSCL 11D

888-22101

Unclas
G5/24 0141234

Nippon Kinzoku Gakkaishi (Japan Institute of Metals
Journal) Vol. 50, No. 6, 1986, pp. 583-589

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON D.C. 20546 MAY 1988



Report Documentation Page

1. Report No. TT-20171	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle APPLICATION OF COPPER-CARBON FIBER COMPOSITES TO POWER SEMICONDUCTOR DEVICES		5. Report Date MAY 1988
		6. Performing Organization Code
7. Author(s) Keiichi KUNIYA, Hideo ARAKAWA, Tadashi SAKAUE, Hitoshi MINORIKAWA, Kenji AKEYAMA, Tatsuji SAKAMOTO		8. Performing Organization Report No.
		10. Work Unit No.
9. Performing Organization Name and Address National Aeronautics and Space Administration Washington, DC 20546		11. Contract or Grant No. NASW-4307
		13. Type of Report and Period Covered translation
12. Sponsoring Agency Name and Address NASA - LEWIS RESEARCH CENTER - LIBRARY		14. Sponsoring Agency Code
15. Supplementary Notes Transl. from JAPANESE to ENGLISH. Nippon Kinzoku Gakkaishi (Japan Institute of Metals Journal) Vol. 50, No. 6, 1986, pp. 583-589. Transl. by SCITRAN, Santa Barbara, CA 93150.		
16. Abstract The title composite was applied to several power semiconductor devices, for example, resin molded diodes, button-type diodes, stud-type diodes, power modules, and integrated circuit ignitor modules. The properties of these power semiconductor devices compared favorably with those con- ventional devices using Mo or W electrodes. In thermal fatigue tests, no degradation in the electrical and mechanical characteristics of these devices was observed. The new composite electrode with C fibers satis- fies all of the major requirements for the electrodes in power semi- conductor devices.		
17. Key Words (Suggested by Author(s))		18. Distribution Statement unclassified-unlimited
19. Security Classif. (of this report) unclassified	20. Security Classif. (of this page) unclassified	21. No. of pages 17
		22. Price

583

Received December 23, 1985.

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The copper-carbon fiber composite (hereinafter referred to as Cu-C fiber composite) possesses the excellent electric and thermal conductivity of copper and the small thermal expansion coefficient of carbon [1-9]. Especially in terms of the small thermal expansion coefficient and high thermal and electric conductivity, its application as new supporting electrodes for power semiconductor devices, replacing tungsten and molybdenum as well as the development of devices with new structures could be expected. We constructed devices equipped with Cu-C fiber composite, tested them for their durability and their applicability was studied.

A power semiconductor device is maintained at a temperature relatively higher than room temperature by the heat generated from silicon pellets, and is subject to thermal cycle due to starting and stopping of the system. When the structural material does not deteriorate, the durability of power semiconductor devices is dependent on the durability of the solder prior to its metal fatigue. Thus, the degree of thermal fatigue when Cu-C fiber composite is incorporated in a power semiconductor device, in comparison with molybdenum in current use, was studied by computer simulation using the 1C igniter module for automobiles as an example [10,11].

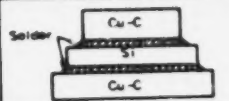
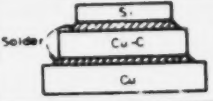
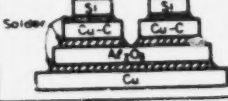
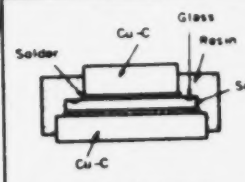
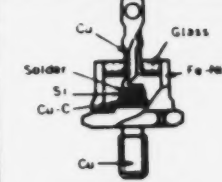
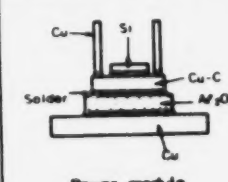
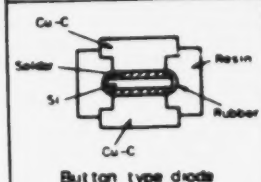
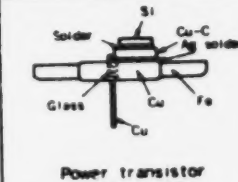
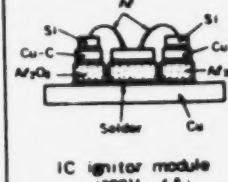
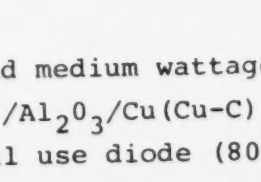
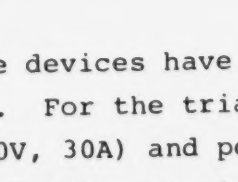
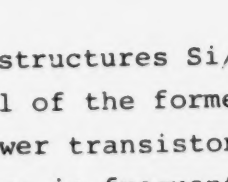
II. EXPERIMENTAL METHOD

1. Trial construction of power semiconductor devices

Power semiconductor devices could be classified into large wattage devices and small and medium wattage devices. The conventional large wattage device contains Cu/Si/W(Mo)/Cu, with an external ceramic sealing. In the present study, in constructing trial models of new devices with Cu-C fiber composite, the conventional W(Mo)/Cu electrodes were replaced with Cu-C electrodes, as shown in Table 1, directly molded with resin. For trial devices utilizing Cu-C fiber composite, resin molded diode (1200V-300A)

and button type diode (300V, 150A) were constructed. In order to facilitate adhesion, the trilayer membrane of Cr-Ni-Ag was vaporized on the surface of silicon pellets. The adhesion between silicon pellets and Cu-C electrodes was accomplished by soldering.

TABLE 1. Trial manufacture of semiconductor devices using Cu-C composites

Basic structures of semiconductor devices	Large wattage devices		Small and medium wattage devices	
				
Fiber arrangement	Spiral		Plain weave, Bidirection	
				
Types of trial devices				
				

The small and medium wattage devices have structures Si/(Cu-C/Cu, or Si/(Cu-C)/Al₂O₃/Cu(Cu-C). For the trial of the former structure, general use diode (800V, 30A) and power transistors (100V, 15A) were constructed. The latter structure is frequently seen in modules carrying large numbers of silicon pellets. For its trial, power module (1200V, 300A) and IC ignitor module (300V, 6A) were constructed. The trilayer membrane of Cr-Ni-Ag was also applied on surfaces of silicon pellets. The surface of Al₂O₃ plate was coated with W-Ni bilayer membrane.

When Cu-C fiber composites are utilized in semiconductor devices, two dimensional isotropy is necessary, at least within a side [1]. Directional structure of fibers to attain two

dimensional isotropy include spiral, bidirectional and reticular arrangements. Comparing these arrangements, the spiral type has small thermal expansion coefficient and high electric and thermal conductivity, but has a shortcoming in that since it has continuous carbon fibers arranged in a special form, it cannot be manufactured into desired shapes [1,2]. Accordingly, this type of composite was utilized in large wattage devices, using 54 vol % of fibers, considering the thermoexpansion characteristics. On the other hand, reticular and bidirectional composites have lesser degrees of desirable characteristics of composites, but could be manufactured into any shape desired, thus utilized in small and medium wattage devices. In these cases with small and medium wattage devices, smaller silicon pellets are used so that thermal stress due to thermal expansion differences is relatively small. Accordingly, since no significant difference exists in fatigue desirability of solder over the range of carbon fibers 35-54 vol %, the amount of fibers was set at 35 vol %, placing emphasis on thermal conductivity. The fibers used are high strength fibers of the PAN system [1].

2. Testing methods of evaluation of reliability of semiconductor devices

In order that Cu-C fiber composites could be utilized in semiconductor devices, thermal resistance of devices should become less than that of conventional devices, and in addition, reliability evaluation tests should show satisfactory performance. Accordingly, tests shown below were performed.

(1) Measurements of thermal resistance: Thermal resistance is a reverse concept of thermal conduction, and is defined as the degree of temperature elevation per unit of electric power consumed at the semiconductor contact point. Thus, devices with less thermal resistance show less temperature elevation of silicon pellets and greater wattage could be attained with the same area of contact.

In semiconductor devices, transitional thermal resistance R could be obtained from equation (1)

$$R = (\Delta T_j - \Delta T_s) / \Delta P \quad (1)$$

where ΔT_j is change in temperature at silicon pellet contact, ΔT_s is change in temperature of a reference point (such as copper cooling fin), when a change in electricity loss ΔP is applied [12,13].

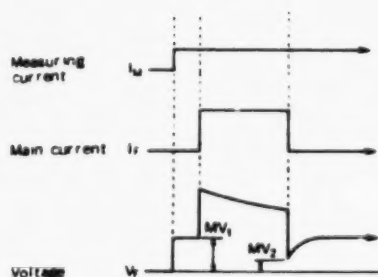


Figure 1. Measuring process of thermal resistance

Figure 1 shows the measuring process of thermal resistance. A small amount of measuring current I_M (to the forward direction) not to cause temperature elevation at a contact point was passed, and lowering of voltage MV_1 was obtained. Next, main current I_F was passed to cause heating of devices, then switched again to measuring current

I_M , and a reduction in voltage MV_2 was obtained. When the difference of MV_1 and MV_2 is designated as ΔmV , equation (2) follows. Hence, in accordance with testing criteria, the duration of time main current I_F was passed through devices was set at 180s for large wattage, and 200 ms for small and medium wattage devices.

$$\Delta mV = MV_1 - MV_2 \quad (2)$$

Since the relationship:

$$\beta \cdot \Delta mV = T_j \quad (3)$$

holds between thermal coefficient β of sequential lowering of voltage (FVD) and ΔmV and ΔT_j [12,13], thermal resistance R was computed by equation (4), obtained from equations (1)-(3).

$$R = (\beta \cdot \Delta mV - \Delta T_s) / \Delta P \quad (4)$$

ΔT_s was obtained from reading of variations in electricity generation of the copper-construction thermoelectric couple attached to the back surface of the copper fin. Also, ΔP is a product of forward electric current and sequential lowering of voltage. For thermal resistance measurements, a ΔmV tester was used with a built-in

microcomputer that automatically measures and computes ΔT_s , ΔmV , ΔT_j and thermal resistance.

(2) Test for endurance to applied pressure: When large wattage devices are incorporated in a system, contacts of electric current terminals, cooling fans, are made under applied pressure. If the applied pressure is small, thermal resistance between the electrode and terminals and cooling fins increases. In a preliminary experiment, it has been confirmed that thermal resistance became constant when applied pressure is 4 MPa or more. Thus, giving a margin, the target applied pressure for the resin mold type diode was set at 10 MPa. The caliber of the device is small with button diodes. Then, the area of contact becomes smaller, and if applied pressure is small, the cooling fin slips so that the same degree of load as that for the resin mold type was applied. As the applied pressure, this corresponds to 21.6 MPa.

The endurance to applied pressure is tested by inserting devices to curve traces connected to an apparatus equipped with a spherical stand. Using the Amsler type all-purpose tester, predetermined load was applied while confirming the pressure or absence of deterioration of pressure endurance of devices. Those satisfying the target pressure applied were taken as passing the test.

(3) Test for temperature cycle: This is a test for the degree of device deterioration with temperature change of external environment. With maximum of 800 testing over the range of (218-233) K - room temperature - 423 K, variations of thermal resistance as well as the presence or absence of pressure duality were studied, and those not showing variations before and after the testings were taken as passing. The standard testing temperatures on the low temperature side are designated as 233 K for large wattage devices, and 218 K for small and medium wattage devices, then these values were used for the testing.

(4) Test for power cycle: This is a test simulating temperature elevation due to internal heating of devices and cooling upon stopping when electric current is turned on and off. Under the conditions of temperature difference (ΔT) at 70-90 K, the maximum number of 3×10^4 tests were made. Those showing no abnormalities in pressure endurance and thermal resistance, when ΔmV , FVD and leak current were within the permissible ranges of values, were designated as passing. The permissible values of leak current are within 10 times the incidental values. The permissible values of ΔmV and FVD were variable with different devices. For example, while ΔmV of large wattage and small and medium wattage devices were within 1.5 and 1.1 times the incidental values respectively, those for general purpose diodes, were within 1.1-1.5 times. Similarly, differences in testing temperature (ΔT) varied with devices, the overall values of ΔT for all testing devices were within 70-90 K.

(5) High temperature reverse bias test: State of deterioration of devices held at 423 K, to which 100 or 800 V of reverse voltage is impressed, was tested. The devices passed included those with ΔmV , FVD and leak current within 1.3-1.5, 1.15 and 2-10 times the initial values respectively. As well as for the power cycle test, different devices have different testing standards so that the ranges of permissible values include the total of all testing devices.

(6) Test for high temperature exposure: State of deterioration of devices exposed to high temperature (423K, 3.6 Ms) for a long period of time was tested. Variations in pressure endurance, ΔmV , FVD and leak current were studied under the conditions similar to those for the high temperature reverse bias test.

(7) Test for low temperature exposure: State of deterioration of devices exposed to low temperature (218K, 3.6 Ms) for a long period of time was tested. Those with ΔmV within 1.3 times the initial values were taken as passing.

(8) 100 cycle surge test: This is a test to study deterioration when a large amount of electric current is passed momentarily under high temperature. At 423 K, 380A of alternative current was passed 100 times for 10 Ms, followed by pauses of 10 Ms, and variations in ΔmV , FVD and leak current were studied. The conditions of deterioration were the same as those for high temperature exposure tests.

(9) High temperature, high humidity test: Deterioration of devices under these conditions was studied. Variations in thermal resistance after 358K, 85% RH, 3.6 Ms, were studied.

(10) Automobile operational testing: For the IC ignitor module, operational testing in automobiles was carried out in order to reproduce the condition when these modules are actually mounted on automobiles.

3. Prediction of fatigue durability

When thermal cycle is applied to a semiconductor device, cracks are formed in the colder adhesive layer due to the difference in thermal expansion among semiconductor components. Generally, these cracks develop at the edge of the adhesive layer where distortion is greatest, then spread centripetally. Accordingly, the solder adhesive layer starts exfoliating from its edges (hereinafter the rate of such exfoliation will be referred to as solder exfoliation rate), the heat generated with silicon becomes more difficult to dissipate, thus temperature rises, properties deteriorate, leading to damage [14-17].

In order to compare solder fatigue durabilities with Cu-C fiber composite and when Mo is used, using the IC igniter module as an example, predictions were made with the prediction program of durability of multilayers and connection parts (HISET... Hitachi Semiconductor Thermal Strength Design Programs) [14]-[17].

This program has been applied on the IC igniter modules in current use and 3 phase diode modules with good results. When structure dimensions, component material constants (Young's rate, Poisson ratio, linear expansion coefficients, yield stress) of the device are entered, distortion, solder exfoliation rate, and rate of increase in transitional thermal resistance are computed and displayed.

III. EXPERIMENTAL RESULTS AND DISCUSSION

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1. Evaluation of reliability of semiconductor devices

Figure 2 shows the relationship between thermal resistance and carbon fiber volume fractions in the resin mold type diode, using spiral Cu-C fiber composite. For comparison, thermal resistance values of the conventional flat package type diode were also shown. As could be seen from the figure, thermal resistance increases as a function of carbon fiber volume fraction. For example, thermal resistance of the device was 0.01 kW when carbon fiber volume fraction was 35 vol %, but increased to 0.02 kW when the fiber volume fraction was 54 vol %. However, even when Cu-54 vol % C was used as the supporting electrode, thermal resistance is about 1/2 less than that of the conventionally structured diode (about 0.04 kW).

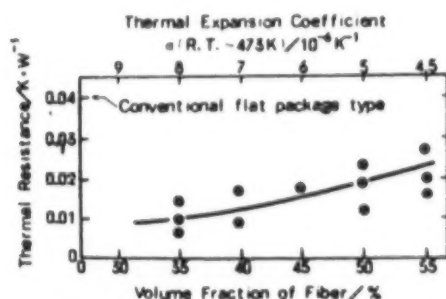


Figure 2. Thermal resistance vs. volume fraction and thermal expansion coefficient for spiral composites.

Figure 3 shows the results of power cycle testing of resin mold type diode using spiral composite with Cu-54 vol % C. Deterioration due to applied pressure was not noted after $2.5 \text{ cycle} \times 10^4$ times testing. The ΔmV and FVD reach the peak at 1.7×10^4 times, but the values were below the tolerable levels even after the targeted 2.5×10^4 times.

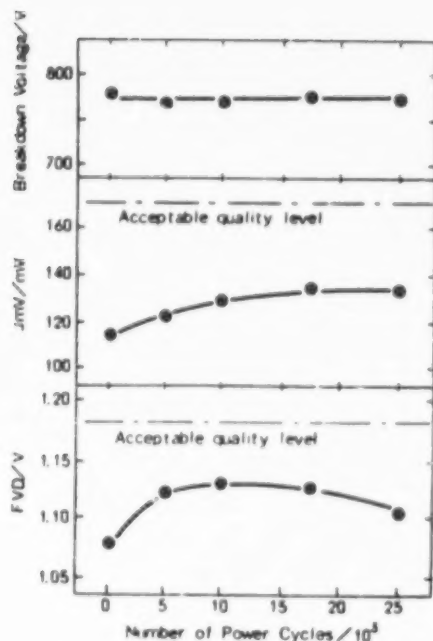


Figure 3. Effect of power cycle test (303 K-373 K) on characteristics of resin molded diode using spiral composite.

Figure 4 shows results of temperature cycle testing of the diode noted above. The determination criterion of temperature cycle was 5 cycles, but results of testing to 75 cycles showed no abnormality in pressure endurance. When Cu-C fiber composite with irregular fiber orientation was used, pressure durability deteriorated at 5 cycles. When V-I characteristic curves of normal and deteriorated devices are compared, the normal device showed normal V-I characteristic curves while the deteriorated device showed rapid increase in electric current. This suggests an increase in leakage of electric current due to cracks in the silicon pellets.

Figure 5 shows the results of high temperature reverse bias test and higher temperature storage test of the button diode using spiral Cu-54 vol % C fiber composite. In high temperature reverse bias testing, 423K - 3.6Ms with 100V caused no changes

A.

No.	Number of Temperature Cycles					Legend	
	0	20	40	60	80		
1	○	○	○	○	○	For regular orientation	
2	○	○	○	○	○		
3	○	○	○	○	○		
4	○	○	○	○	○		
5	○	x				For irregular orientation	
6	○	○	x				

B)

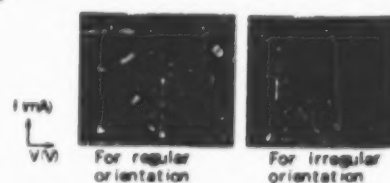


Figure 4. Effect of fiber orientation on temperature cycle test (233 K-R.T.-423 K) of resin molded diode using spiral composites.

A--Fiber orientation vs. temperature cycles.

B--V-I diagrams after temperature cycle test.

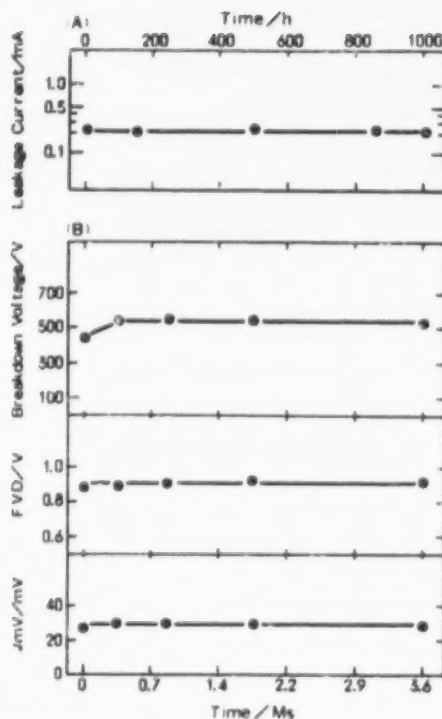


Figure 5. Effect of test conditions (A) and (B) on characteristics of button type diode using spiral composite.

A--endurance testing with reverse bias (-100V) applied at high temperature (423K);

B--high temperature storage test (423K, 3.6 Ms)

in leakage current, and no abnormalities were noted. Also with high temperature storage testing, no virtual changes were noted in pressure durability, FVD and ΔmV . With pressure endurance testing, application of 49 MPa, twice the target pressure, caused no change in the device.

Table 2 shows test results on general purpose diodes. With all the testing, variations in ΔmV , FVD and leakage current before and after the testing were within the criteria for determination.

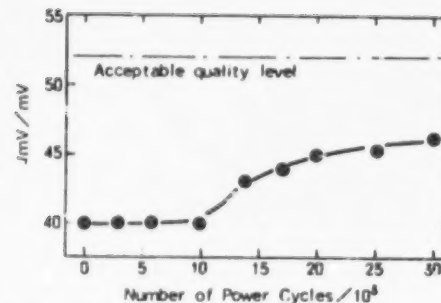


Figure 6. ΔmV vs. power cycles (303K-393K) for power transistor using plain weave composite

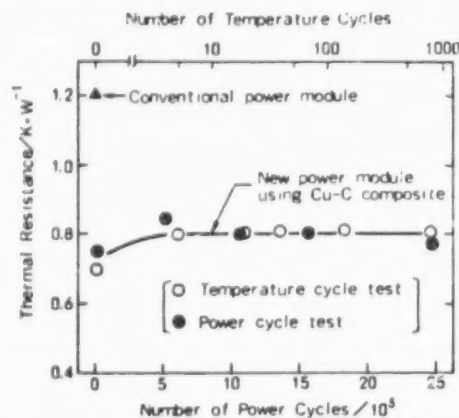


Figure 7. Thermal resistance vs. power cycles (328K-413K) and temperature cycles (218K-R.T.-423K) for power module using plane weave composite.

TABLE 2. Test results on stud type diode using plain weave composite for the most strict requirement

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Test parameters	Test condition	FVD/V		JmV/mV		Leakage current/ μ A	
		Before	After	Before	After	Before	After
Power cycle test	298-568K/JT:70K/ 10k cycles	1.18	1.19	50	50	1	1
High temperature storage test	423K, 3.6 Ms	1.19	1.19	50	50	1	1
Endurance testing with reverse bias applied at high temperature	423K, 800V 3.6 Ms	1.20	1.20	51	51	2	2
Endurance testing with 100cycles surge current application	423K, 580A 100cycles	1.19	1.19	51	52	2	2
Thermal resistance	I_f : 30A I_w : 0.1mA Time : 10ms	0.47 K $\cdot$ W $^{-1}$ Mo : 0.55 K $\cdot$ W $^{-1}$					

Figure 6 shows effects of power cycle on ΔmV of the power transistor. When the numbers of cycle exceed 1×10^4 times, some elevation in ΔmV was noted, but its extent was small, and even at 2×10^4 times, which was the criterion for power cycle testing, the increase was within the tolerable range. Thus testing was extended to 3×10^4 times, but the result similarly fell within the tolerable range. Other testing also fulfilled the criteria.

Figure 7 shows variation of thermal resistance of power modules in temperature cycle and power cycle testings. Thermal resistance was less than that of the conventional model using Mo, and the values before and after testing showed virtually no difference.

Figure 8 shows a comparison of power cycle testing of LC igniter modules that used new structures with Cu-C fiber composites and that used conventional Mo. Changes in thermal resistance were within the accepted quality level for both models. Comparing the two models, thermal resistance values were similar from initial value to 2000 cycles, but at 3000 cycles, the thermal resistance of the new model using Cu-C fiber composites showed no virtual increase,

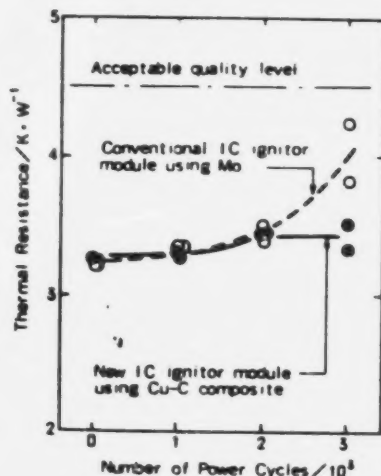


Figure 8. Comparison of new IC ignitor module using plain weave composite with conventional one using Mo in the power cycle test (303K-393K).

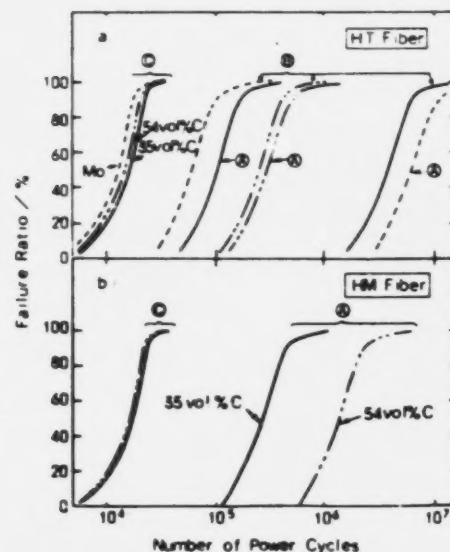
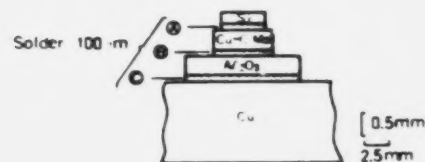


Figure 9. Thermal fatigue lines of bonded layers of new IC ignitor module using plain weave composites in the power cycle test (303K-393K).

while that of the conventional model increased. This is probably due to the greater solder exfoliation rate with the conventional model in comparison with the new model with Cu-C fiber composites, and with repeated application of power cycles, edges of solder connecting parts started exfoliating, thus impairing the dissipation of heat generated in silicon, leading to elevation of temperature and increase in thermal resistance, as will be mentioned below, under the prediction of solder fatigue durability with the IC ignitor module. In addition to the power cycle testing, high temperature-high humidity testing as well as testing on automobiles over several thousand Km were carried out and no abnormalities were noted.

From the foregoing, various test models of semiconductor devices using Cu-C fiber composites were constructed, and were subjected to reliability evaluation testing. The results showed

superior thermal resistance as well as reliability, and it was determined that the Cu-C fiber composites could be utilized in semiconductor devices.

2. Prediction of solder fatigue durability

Figure 9(a) shows solder fatigue durability of IC ignitor module that used high strength (HT) fiber, as a function of number of power cycles (temperature 303-393K, $\Delta T: 90K$) and solder exfoliation rate. The electrodes used were Mo, CU-35 vol % C, and CU-54 vol % C. For each electrode, the durability is minimal at the Al_2O_3/Cu connection, with that of the Mo electrode the shortest, followed by Cu-54 vol % C, and Cu-35 vol % C. The durability of Si/Cu-C connection (A) decreased with a decrease in carbon fiber volume, but even with Cu-35 vol % C, the value is one figure greater compared to that for the C. Contrariwise, the duration of Cu-C/ Al_2O_3 connection (B) was greater with less volume of carbon fiber. /589

When high elasticity (HM) fiber was used, as shown in Figure 9(b), values for the C were virtually identical with those for high strength (HT) fiber, and for each type of fiber, the number of power cycles that reached solder exfoliation rate of 80% was above 2×10^4 times. The durability of the A increased about a figure, in comparison with HT fiber.

The solder fatigue durability in the IC ignitor module using Cu-C fiber composites was studied as above. The durability of the Cu/ Al_2O_3 connection was the shortest, and was about 2×10^4 times regardless of the type or volume of carbon fibers. However, these values were about 2×10^3 times greater than when Mo was used. From these data and computations, it was noted that Cu-C fiber composite could be used as an alternative to Mo in semiconductor devices such as IC ignitor modules.

IV. CONCLUSION

Reliability tests of various semiconductor devices equipped with Cu-C fiber composite were carried out, and the prediction of solder fatigue durability was studied, and the following findings were obtained.

(1) Test models of large wattage devices using spiral Cu-C fiber composite (resin mold type diode, button diode) and small and medium wattage devices using reticular Cu-C fiber composite (general purpose diode, power transistor, power module, IC ignitor module) were constructed. It was noted that these devices had superior thermal resistance and reliability, and it was determined that Cu-C fiber composite could be used in semiconductor devices.

(2) Using the IC ignitor module as an example, predictions were made of solder fatigue durability of semiconductor device using Cu-C fiber composite. The results suggested an equal or better fatigue durability than the currently used model could be obtained.

At the end, deep appreciation is expressed to Dr. Komei Yano, Senior Researcher, Hitachi Research Laboratory, Hitachi Ltd, who constructed and tested power modules.

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